Optimization Design of a Parallel Flow Field for PEMFC with Bosses in Flow Channels

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Abstract: The proton exchange membrane fuel cell (PEMFC) is a promising energy conversion device due to its high reliability, fast response speed, and low pollutant emission. However, the reality of its commercial application requires further cost reduction and efficiency improvement. The material distribution in the channel and the performance of PEMFC can be improved by setting the boss inside the flow channels. In this paper, the performance of PEMFC with the boss in flow channels in a parallel flow field was analyzed by simulation. The influence of different boss arrangements and heights on gas pressure drop, distribution uniformity, gas component distribution, temperature distribution, and output performance of the fuel cell were analyzed in detail. The bosses would increase the pressure drop and the distribution uniformity of reactive gases in flow channels significantly. The cross-arrangement of bosses is better than the cross-arrangement of bosses and juxtaposition according to increasing performance and pressure drop. The cross-arrangement with a boss height of 0.4 mm is suitable for the parallel flow field in this paper. The improved scheme of flow channel design is proposed to provide a reference for fuel cells for subsequent research.

Keywords: parallel flow field; PEMFC; boss; pressure drop

1. Introduction

The energy structure of modern society is dominated by fossil fuels. On the one hand, fossil fuels are non-renewable resources that will eventually be exhausted. On the other hand, the massive consumption of fossil fuels emits plenty of greenhouse gases, causing many environmental problems. Therefore, there is a growing need to seek out new renewable energy sources. Among many renewable resources, hydrogen energy is regarded as the subversive direction of the future energy revolution due to its advantages of wide sources, zero-emissions, and high energy density [1]. In many hydrogen energy utilization technologies, the hydrogen fuel cell has become an essential link in the process of hydrogen energy utilization due to its advantages of high efficiency, long life, and strong endurance capability. With the continuous development of China’s goal of “achieving carbon peak and carbon neutrality”, hydrogen fuel cells have attracted much attention. As a key component of hydrogen fuel cells, the bipolar plate has functions such as isolation of reactants, formation of reactant channels, drainage, heat dissipation, etc. Its configuration affects the performance of the flow field directly and thus affects the performance of the whole battery. The high-performance flow field configuration makes the reaction and temperature distribution of all parts of the battery as even as possible while taking into account good drainage performance and appropriate flow field pressure drop, which significantly improves the utilization rate of the active area inside the battery and improves the efficiency and life of the battery.

The traditional flow field configurations mainly include parallel flow fields, serpentine flow fields, and interfinger flow fields. The serpentine flow field and interfinger flow field...
have large pressure drops but good drainage performance. The parallel flow field has a small pressure drop and is easy to manufacture, but the battery has poor performance and poor drainage performance. The specific configuration is shown in Figure 1. Especially for the configuration of a flow field with a large active area, the disadvantages of a parallel flow field are particularly obvious. The built-in boss can improve the uneven gas distribution, temperature distribution, and poor drainage performance of the parallel flow field while maintaining the advantages of the parallel flow field. In this paper, the layout and height of the boss in a parallel flow field are studied to provide ideas for the plate design of a large-area flow field.

![Figure 1](image_url)

**Figure 1.** Traditional flow field structure. (a) parallel flow channel; (b) serpentine flow channel; (c) interfinger flow channel.

At present, the traditional flow field structure modification design can be roughly divided into three kinds. The first is the modification of flow channel geometric parameters, such as flow channel section shape and flow channel transition fillet. The second is to add a separator and boss inside the flow channel to change the mass transmission inside the flow field and then change the output performance of the PEMFC. The third is the design of new flow channels, or bionic flow channels, such as three-dimensional flow fields, wavy flow fields, and bionic honeycomb flow fields.

At present, scholars have carried out a lot of research on the traditional flow channel configuration design. Chiu et al. [2] analyzed the influence of structural parameters such as width, height, and aspect ratio of the parallel flow channel, serpentine flow channel, and interdigital flow channel. Rostami et al. [3] conducted a simulation and experimental study on the influence of the diameter of the curved part of the serpentine flow channel on the overall performance of the fuel cell. The study found that when the curved diameter was 1.2 mm and the working voltage was 0.6 V, compared with 1 mm and 0.8 mm, the battery power increased by 0.82 and 1.78%, respectively. Yan et al. [4] quantitatively studied the influence of baffle blocking ratio and the number of baffles on fuel cell performance and found that a large baffle blocking ratio consumes greater gas pumping energy, and excessive baffles will affect gas transportation downstream. Marappan et al. [5] introduced many modified, hybrid, and new flow field designs of the PEMFC. Dong et al. [6] studied the mass transfer effect of different shaped blocks in fuel cells and found that the flow performance of semi-elliptical blocks was the best, and the effective power was increased by 15.77% compared with traditional flow channels. Hasan et al. [7] experimented with three types of gas flow channels to optimize fuel cell performance. Ebrahimzadeh et al. [8] studied the shape and size of baffle plates (including rectangle, triangle, and trapezoid) through simulation, aiming at the distribution of reactants in fuel cells and the performance of fuel cells. They found that when the working voltage was 0.6 V, the performance of fuel cells with blocking blocks was 50% higher than that of ordinary fuel cells. The corresponding runner structure design is shown in Figure 2.
In addition to improving the geometric parameters of the traditional flow channel and adding barriers and blocks, researchers have also studied some new flow channels. Li et al. [9] studied the wavy flow channel and found that it performed better than the traditional snake flow channel in promoting oxygen diffusion and liquid water transmission. Atyabi et al. [10] proposed a honeycomb cathode channel and studied the transmission characteristics of fuel cells based on a three-dimensional PEMFC model. The simulation results show that the new honeycomb channel design can improve the pressure and temperature distribution inside the fuel cell and reduce the possibility of flooding in the catalytic layer. Afshari et al. [11] simulated a fuel cell with parallel flow channels and metal foam as a flow distributor to improve the cell’s performance. Fatemeh et al. [12] studied the fuel cell’s performance with an interdigitated flow channel.

In summary, the geometric parameters of the flow channels have a great effect on the performance of fuel cells. In this paper, several schemes of parallel flow fields with different boss arrangements in flow channels were proposed, and numerical simulations were made to compare and analyze the effects of different boss arrangements on the uniformity of reactive gas distribution, pressure drop, and current density of fuel cells. Finally, a modified scheme of boss arrangement for the parallel flow field was obtained.

2. Numerical Setup

2.1. The Establishment and Verification of the Grid Model

The plate model adopted in this paper is shown in Figure 3. The plate region is roughly divided into several parts, namely hydrogen, coolant, and air inlet and outlet, diversion zone, and parallel flow field zone. Among them, a cylindrical transition diversion is adopted in the diversion zone, which aims to make the reaction gas reach a uniform distribution of speed and flow at the entrance of each flow channel as far as possible before entering the flow channel. The cross-sections of all channels in the parallel flow field are rectangular, and the spacing of each channel is equal.

The parameters of other components except the plate are shown in Table 1. In addition, it is also necessary to design the height and arrangement of the boss inside the flow channel. Previous studies have shown that insufficient oxygen diffusion at the cathode side is one of the main factors limiting the output power of fuel cells [13], but this is not the case for anode measurement. Therefore, the boss is mainly arranged at the cathode side, and a parallel flow field without the boss is still adopted at the anode side. In addition, the height of the boss is set as a gradient of 0.2 mm, 0.4 mm, and 0.6 mm, and the layout is set as staggered and parallel.
The grid model uses structured grids to make the grid in the fluid domain finer and the grid in other regions rougher, which reduces the consumption of computing resources and improves computing efficiency. The specific grid model is shown in Figure 4.

![Grid model](image)

**Figure 4.** Fluid-solid-electrical coupling grid division diagram. (a) Plate grid diagram; (b) flow field grid diagram; (c) local magnification of membrane electrode grid; (d) global grid diagram.

To save computing resources and time, grid independence verification should be carried out to make the number of grids as reasonable as possible. The parallel flow field without boss was taken as an example to verify the grid independence, and the CFD simulation models with the quantities of grids of 4,531,331, 6,027,930, 7,633,102, 8,514,135 and 9,803,004 were established, respectively. The simulation calculation was carried out under the condition that the battery output voltage was 0.6 V. The current density obtained is shown in Figure 5.

As shown in Figure 5, when the quantity of grids is greater than 7,633,102, the increase in grids will not lead to changes in battery current density. Therefore, when the quantity of model grids is near 7,633,102, the computational grids will maintain high precision and not waste too many computing resources. Thereafter, the size and quantity of model grids should be set close to this quantity.

The flow field configuration of the test model is consistent with that of the simulation model, and the active area is 95 cm², as shown in Figure 6. The membrane electrode assemblies (MEA) of the single fuel cell are made by W. L. Gore and Associates, Inc., Newark, DE, USA, and the thickness is 45 µm. The platinum loading capacity of the cathode is 0.4 mg·cm⁻², and that of the anode is 0.1 mg·cm⁻². The carbon paper is made by SGL Carbon Company in Meitingen, Germany, with a thickness of 285 µm. The test
platform was made by Greenlight Innovation company in Burnaby BC, Canada, as shown in Figure 7.

![Figure 5](image_url) **Figure 5.** Grid independence verification of fluid simulation with different mesh quantities.

![Figure 6](image_url) **Figure 6.** Test to verify the use of the plate runner part of the physical map.

![Figure 7](image_url) **Figure 7.** Physical picture of the fuel cell test system.

During the test, the fuel cell operating temperature was 75 °C, the operating pressure was 2 atm, the hydrogen relative humidity is 30%, the oxygen relative humidity was 50%, and the hydrogen oxygen stoichiometric ratio was 1.5 and 2.5, respectively.

Figure 8 shows the comparison of polarization curves obtained by simulation and experiment. The overall variation trend of simulation value and test value is the same, the overall error is small, and the maximum error is 4.42%, which is within the allowable range. It can be seen from the figure that under the same voltage, the current density obtained by the test is less than the simulation value, which may be caused by the neglect of assembly resistance and leakage voltage and other losses during simulation. In addition, the local error of the test value may increase suddenly, which is related to the battery voltage fluctuation during the test.
overall error is small, and the maximum error is 4.42%, which is within the allowable range. It can be seen from the figure that under the same voltage, the current density obtained by the test is less than the simulation value, which may be caused by the neglect of the heat generation range. Figure 8. Comparison of simulation and test values.

2.2. Mathematical Model and Basic Assumptions

2.2.1. Basic Governing Equation

The basic governing equations of proton exchange membrane fuel cells can be summarized into four equations: mass conservation equation, momentum conservation equation, energy conservation equation, and component conservation equation [14,15].

During the fuel cell operation, the mass of each component is conserved, and the mass conservation equation applies to all components in the fuel cell, as shown in Equation (1).

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot \left( \rho \vec{v} \right) = 0 \tag{1}
\]

\( \rho \) is the density; \( \vec{v} \) as the velocity vector; \( \nabla \) is Laplace; The right side of the equal sign should be the mass source term, which is 0 for the gas diffusion layer and fluid domain of the proton exchange membrane fuel cell.

Using Stokes’ law of incompressible fluids, the momentum conservation equation for proton exchange membrane fuel cells can be obtained as Equation (2).

\[
\frac{\partial \left( \rho \vec{v} \right)}{\partial t} + \nabla \left( \rho \vec{v} \vec{v} \right) = -\nabla p + \nabla \left( \mu_{\text{eff}} \nabla \vec{v} \right) + S_m \tag{2}
\]

where \( p \) is fluid pressure and \( \mu_{\text{eff}} \) is the average viscosity of the mixture. \( S_m \) is the momentum source term. For fuel cell in the gas channel \( S_m = 0 \), in the gas diffusion layers and catalyst layers \( S_m = -\frac{F}{V} e \vec{v} \), including \( K \) for gas diffusion layer and catalyst layer permeability, and \( \varepsilon \) for gas diffusion layer of porosity.

The energy conservation equation for any region in a proton exchange membrane fuel cell can be described using Equation (3).

\[
(\rho c_p)_{\text{eff}} \frac{\partial T}{\partial t} + (\rho c_p)_{\text{eff}} (\vec{v} \nabla T) = \nabla \left( k_{\text{eff}} \nabla T \right) + S_e \tag{3}
\]

\( c_p \) is the average specific heat capacity of the mixture; \( T \) is the temperature; \( k_{\text{eff}} \) is effective thermal conductivity; \( S_e \) is the energy source term, which includes heat of electrochemical reaction, heat of polarization, and heat of phase transformation. The subscript \( \text{eff} \) indicates the effectiveness of porous media.

The working process of proton exchange membrane fuel cells is accompanied by the consumption and generation of substances. The Equation (4) characterizing the conservation of single gas phase components is:

\[
\frac{\partial (\rho \varepsilon x_i)}{\partial t} + \nabla \left( \vec{v} \rho \varepsilon x_i \right) = \nabla \left( \rho D_{i}^{\text{eff}} \nabla x_i \right) + S_{si} \tag{4}
\]
In the above equation, \( x_i \) is the component gas mass fraction, where \( i = 1, 2, \ldots, N \); \( D_{\text{eff}}^i \) is the effective diffusion coefficient, which is a function of the porosity (\( \varepsilon \)) and the tortuous rate (\( \tau \)). \( S_{\eta} \) is a component source or sink. The first two terms of the component conservation equation represent the component accumulation and convection terms, while the first term on the right side of the equation represents the Fickian law in porous diffusion, which is mostly described by the Maxwell-Stefan equation, which can analyze convection transfer, diffusion transfer, and migration transfer in an electric field.

In the component conservation equation, the source term \( S_{\eta} \) is 0 except in the catalytic layer, while in the catalytic layer, where the electrochemical reaction consumes or produces components, the source terms of hydrogen, oxygen, and water are shown in Equations (5)–(7), respectively.

\[
S_{\text{H}_2} = -i_a \frac{M_{\text{H}_2}}{2F} \\
S_{\text{O}_2} = -i_c \frac{M_{\text{O}_2}}{4F} \\
S_{\text{H}_2\text{O}} = -i_c \frac{M_{\text{H}_2\text{O}}}{2F}
\]

where, \( i_a \) and \( i_c \) represent the current density of the anode and cathode, respectively. \( M \) represents the molar mass of different substances, respectively, and the species of substances are represented by subscripts; \( F \) for Faraday’s constant, which is 96,485.3383 C/mol.

2.2.2. Electrochemical Equation

The current transmission in proton exchange membrane fuel cells can be described by the charge conservation governing equation, which can be divided into solid phase potential and membrane phase potential according to the type of current transmission, and the charge conservation expressions are respectively shown in Equations (8) and (9) [14,15].

\[
\nabla \cdot \left( k_{\text{solid}}^{\text{eff}} \nabla \varphi_{\text{solid}} \right) = S_{\varphi_{\text{solid}}} \\
\nabla \cdot \left( k_{\text{mem}}^{\text{eff}} \nabla \varphi_{\text{mem}} \right) = S_{\varphi_{\text{mem}}}
\]

where, \( k_{\text{solid}}^{\text{eff}} \) and \( k_{\text{mem}}^{\text{eff}} \) are the conductivity of the solid phase and the film phase, respectively. \( \varphi_{\text{solid}} \) and \( \varphi_{\text{mem}} \) represent the electric potential for the solid and film phases, respectively. \( S_{\varphi_{\text{solid}}} \) and \( S_{\varphi_{\text{mem}}} \) represent the electronic current source item and the proton current source item, respectively. All other parts of the \( \varphi_{\text{solid}} \) are 0 except the anode and cathode catalytic layers. In the anode catalytic layer, \( S_{\varphi_{\text{solid}}} = -i_a, S_{\varphi_{\text{mem}}} = i_a \). In the cathode catalytic layer, \( S_{\varphi_{\text{solid}}} = -i_c, S_{\varphi_{\text{mem}}} = i_c \).

The open-circuit voltage of a proton exchange membrane fuel cell can be determined by the Gibbs free energy corresponding to the maximum electrical energy it can generate. Therefore, the open-circuit voltage can be calculated by the Nernst equation, as shown in Equation (10), as described in [15].

\[
E = -\frac{\Delta G_0}{2F} + \frac{RT}{2F} \ln \left( \frac{P_{\text{H}_2} P_{\text{O}_2}^{0.5}}{P_{\text{H}_2\text{O}}} \right)
\]

where \( \Delta G_0 \) is the change in Gibbs free energy; \( R \) is the gas constant; \( T \) is the temperature; \( P \) represents the partial pressure of each substance, respectively, and the substance type is represented by its subscript.
In addition, the current source term of the anode and cathode in the proton exchange membrane can be described by the Butler-Volmer equation, as shown in Equations (11) and (12).

\[
i_a = j_{\text{ref}_a}^a (T) \left( \frac{C_{\text{H}_2}}{C_{\text{H}_2}^{\text{ref}}} \right)^{\gamma_a} \left( e^{\alpha_a F (E_a - E_{0a})/RT} - e^{-\alpha_a F (E_a - E_{0a})/RT} \right)
\]

\[
i_c = j_{\text{ref}_c}^c (T) \left( \frac{C_{\text{O}_2}}{C_{\text{O}_2}^{\text{ref}}} \right)^{\gamma_c} \left( -e^{\alpha_a F (E_c - E_{0c})/RT} + e^{-\alpha_c F (E_c - E_{0c})/RT} \right)
\]

where \( j_{\text{ref}_a}^a \) and \( j_{\text{ref}_c}^c \) are the reference current density of the anode and cathode, respectively, and the parameter is a function of temperature. \( C \) and \( C^{\text{ref}} \) represent the molar concentration and the reference concentration of the substance, respectively, and the type of substance is represented by its subscript. \( \gamma_a \) and \( \gamma_c \) are the concentration indices of the anode and cathode, respectively. \( \alpha_a \) and \( \alpha_c \) are the current exchange coefficients of the anode and cathode, respectively. \( E_a \) and \( E_c \) are the potentials of the anode and cathode, respectively. \( E_{0a} \) is the potential at equilibrium between the two directions of the electrochemical reaction, and the difference between the two represents the overpotential. \( R \) is the gas constant and \( T \) is the local temperature.

### 2.2.3. Model Simplification and Basic Assumptions

There are complex physical and chemical changes in proton exchange membrane fuel cells, from the input of reaction gas to diffusion, the electrochemical reaction to the charge transfer, and then to the discharge of products and remaining reactants, which often include fluid flow, gas phase diffusion, heat transfer, phase transformation, and electrochemical reaction. In the simulation calculation, all processes are often not simulated completely. To ensure the smooth progress of the calculation process and improve the speed of the simulation calculation, the following assumptions are usually required for the simulation model:

1. The gases involved in the reaction are all ideal gases, satisfying the ideal gas equation of state [16];
2. The fluid-state flow inside the battery is regarded as laminar flow [17];
3. Steady-state operation of fuel cells under different working conditions [18];
4. The materials of each component of the fuel cell are isotropic and homogeneous;
5. The water produced by the reaction is gaseous;
6. The leakage voltage is negligible [19];
7. The resistance between components due to assembly is negligible.

### 3. Results

#### 3.1. The Influence of the Boss Arrangement

In this paper, two schemes of boss arrangement were set up: juxtaposition and cross-arrangement, as shown in Figure 9. There are eight bosses in each flow channel in the two schemes.

#### 3.1.1. Influence on the Distribution of Pressure Drop

The flow state inside the fuel cell determines the mass transmission inside the fuel cell. The poor mass transmission will seriously degrade the performance of the fuel cell. Figure 10 shows the flow field pressure diagram under the different boss arrangements. The flow field section is the middle section of the fuel cell cathode flow field, which can represent the pressure distribution of the whole flow field. Since the height of the boss is 0.4 mm and the total height of the flow channel is 0.6 mm, there is a disconnection area in the flow channel, and the disconnection area is displayed blank in Figure 10. The pressure distribution of the flow field in the three arrangements presents a decreasing trend from the inlet to the outlet, and the highest and lowest values of the pressure are distributed
respectively at the inlet and outlet of the flow field. Because of the viscosity, the fluid needs to overcome the resistance and transmit forward in the flow field. The closer the position is to the inlet, the more the front part of the fluid has to push the back part of the fluid. Thus, the greater the resistance, the greater the pressure. In addition, as shown in the picture, the pressure drop of the flow field increases significantly with the boss structure. The reason is that the cross-sectional area of the flow passage with the boss becomes smaller, and the natural flow resistance will become larger. So the pressure drop will increase, which will also lead to an increase in pump gas power.

Figure 9. Schemes of the boss arrangement diagram, (a) juxtaposition; (b) cross-arrangement.

Figure 10. Pressure drop of the flow field. (a) Without bosses; (b) juxtaposition; (c) cross-arrangement.

Table 2 lists the pressure drop of the flow field in different boss arrangement modes. As shown in the table, the pressure drop is the smallest without the boss (593.15 Pa), the largest when the boss arrangement is in juxtaposition (1584.71 Pa), and the pressure drop between the two in the cross-arrangement (1479.34 Pa). The smaller the pressure drop, the more smoothly the fluid flows in the flow channel, which is not conducive to the convective transmission of the fluid in the flow field. Meanwhile, the smaller the pressure drop, the less pump gas power is required. Therefore, the energy consumption will reduce, and the overall effectiveness of the battery system will increase. The pressure drop is not only
under the influence of the cross-sectional area of the flow field but also the flow state of the fluid in the flow field. Among the results of the three arrangement modes, the pressure drop is the smallest without the boss because of the least flow resistance. The pressure drop of cross-arrangement is smaller than that of juxtaposition. The main reason is that there is a larger disturbance to the fluid in the flow field of the cross-arrangement, which is more conducive to the diffusion of fluid in the gas diffusion layer under the plate ridge. Therefore, more gas will enter the gas diffusion layer, and the pressure drop will become smaller when the gas transmits through the diffusion layer.

Table 2. Pressure drop of the flow field in different schemes.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>No Boss</th>
<th>Juxtaposition</th>
<th>Cross-Arrangement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (Pa)</td>
<td>593.15</td>
<td>1584.71</td>
<td>1479.34</td>
</tr>
</tbody>
</table>

Rectangular is a conventional cross-section of the flow field channel of PEMFC, and the cross-section shape used in this paper is rectangular. The cross-section shape and size of different schemes remain constant. The flow loss when the gas flows along the flow channel varies in two kinds: the linear loss and the local loss. The linear loss is mainly affected by the cross-sectional area and shape of the flow channel as gas flows. All the cross-sectional shapes of different schemes in this paper are rectangular, and all the lengths of schemes are the same, so the effect of cross-sectional area on the linear loss is similar. The local loss is mainly affected by the local change in the cross-sectional area. For the above three schemes, the local loss mainly occurs in the juxtaposition and cross-arrangement schemes. The number and size of the bosses in the two schemes are the same, and only the arrangement is different. Thus, there is a minor difference between the local losses of the above three schemes. In summary, for the sum of the linear loss and local loss, there is little difference between the two schemes of juxtaposition and cross-arrangement, and the no-boss scheme is the smallest.

The pressure distribution reflects the flow resistance of the flow field. The large flow field with a large pressure drop means a large pump loss and more parasitic power in the fuel cell system. However, a small pressure drop is not conducive to the convective transmission of fluid in the flow field, which may decrease the output power of the fuel cell system. Therefore, a reasonable flow field pressure distribution can improve the output power of the whole fuel cell system. For the three schemes involved in this part, the cross-arrangement method has a moderate pressure drop and is more suitable for practical application.

3.1.2. Influence on the Distribution of Flow Rate

The uniformity of gas distribution in each flow channel has a great influence on the performance of the fuel cell. The poor uniformity of gas distribution in the flow field will lead to a large difference in the degree of the electrochemical reaction in each part of the membrane electrode. The area with severe reaction would overheat and flood, which would decrease the performance of the fuel cell system, lead to MEA damage, and shorten the life cycle of the fuel cell. This part analyzes the distribution uniformity of the three schemes. The number of flow channels in each scheme is 61, and the number of flow channels is 1–61. Figure 11 shows a comparison diagram of the flow distribution of different schemes. The cross-section of each flow channel is the area of the entrance side of the flow field. The flow channels are numbered by the distance between the channels and the entrance side. The larger number means the channel is nearer to the entrance side than other channels. As shown in Figure 11, the different trends of flow distribution in flow channels of schemes are similar, a “concave” pattern with more on both sides and less in the middle. Moreover, the gas flow rate near the inlet is significantly higher than that near the outlet. With the higher gas pressure and similar velocity direction to the inlet, more reactive gas will flow through the flow channel near the inlet, and that is the reason for the higher value of
the flow rate near the inlet. With the lower pressure near the outlet and similar velocity direction to the outlet, more reactive gas will flow through the flow channel near the outlet, and that is the reason for the higher value of the flow rate near the outlet. Different from the scheme without a boss, the flow rate of each flow channel is roughly similar in the latter two schemes, and the flow distribution is more uniform. The flow distribution of juxtaposition and cross-arrangement is different, and that of cross-arrangement shows an oscillation trend. The flow rate of the flow channels where the first boss is closer to the inlet is lower than that where the first boss is further from the inlet. The average value of the flow rate of a cross-arrangement is similar to that of juxtaposition, and the uniformity of flow distribution is better than that of the arrangement with no bosses. With the distribution of the gas components, the analysis is more comprehensive in the following part.

Figure 2. Research on adding separator flow channels. (a) Regular arrangement; (b) Zigzag arrangement [8].

Figure 11. Flow distribution diagram of different scheme flow fields.

Two dimensionless numbers, CFR and SD, are introduced to analyze the uniformity of the flow distribution in different schemes.

CFR, Channel Flow Ratio, represents the proportion of the flow rate of an individual flow channel to the average flow rate of all flow channels, as shown in Equation (13).

$$CFR_i = \frac{q_i}{\overline{q}}$$

The subscript $i$ is the serial number of the individual flow channel. $q_i$ is the flow rate of the flow channel, and $\overline{q}$ is the average flow rate of all flow channels.

SD represents the standard deviation of the gas flow rate in all flow channels and shows the non-uniformity of the flow distribution in the flow field as shown in Equation (14).

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(CFR_i - 1)^2}{n}}$$

$n$ is the total number of flow channels. The value of $n$ is 61 in this paper.

When the flow distribution of all flow channels is uniform, the flow rate of all flow channels is almost the same. The value of CFR is about 1, and the value of SD is about 0. Table 3 shows the comparison of flow distribution uniformity of the three schemes. The values of the SD schemes are less than 0.1 for juxtaposition and cross-arrangement, which means good uniformity between the two schemes. The uniformity of juxtaposition is the best, and the one without a boss is the worst.

Table 3. Comparison of the flow distribution uniformity of each scheme.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>No Boss</th>
<th>Juxtaposition</th>
<th>Cross-Arrangement</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD</td>
<td>0.1708</td>
<td>0.0413</td>
<td>0.0738</td>
</tr>
</tbody>
</table>
3.1.3. Influence on the Distribution of Gas Components

Considering the location of the bosses, the data for this analysis is from the interface of GDL and CL at the cathode side. Figure 12 shows the distribution cloud of oxygen mass fraction at the interface with different schemes. As shown in Figure 12, there is an obvious difference between the three schemes. As shown in Figure 12a, the oxygen is concentrated in the left upper part of the flow field near the entrance. The reason is that the distribution of oxygen on the cathode is similar to the distribution of hydrogen on the anode, and the intense electrochemical reaction occurs approximately in the middle part of the flow field along the diagonal. Compared with Figure 12a, there is a more uniform distribution of oxygen in Figure 12b,c. In addition, that shows a significant improvement in uniformity with the help of bosses. The flow resistance of each channel in the flow field is different, although the flow channels have the same instructions. As shown in Figure 12, the gas flows through the entrance distribution area, the flow channels, and the exit distribution area in turn, and the different flow paths lead to different flow resistance and distribution of the gas pressure. The bosses in the channel increase the flow resistance of every flow path containing the channel, and the flow resistance of every flow path tends to become uniform. As shown in Figure 12b, the oxygen mass fraction under the bosses is much higher than the surrounding parts of the channels. As shown in Figure 12c, the oxygen mass fraction under the bosses is similar to Figure 12b, but the distribution is more uniform than Figure 12b. The reason is that the cross-arrangement of bosses increases the row of bosses. In addition, more row of bosses means more times that the gas could be uniform by the bosses in the channel.

Figure 12. Distribution of the oxygen mass fraction. (a) Without bosses; (b) juxtaposition; (c) cross-arrangement.

In PEMFC, the area where the electrochemical reaction is more violent would produce more water and would always accumulate more water. As shown in Figure 13, the distribution of the water mass fraction is almost exactly opposite the distribution of oxygen, which means the consumption of the electrochemical reaction. In addition, compared with Figure 13, the distribution of water is more uniform in the direction perpendicular to the flow channels in Figure 13. The reason might be that the distribution of reactive gases (oxygen and hydrogen) becomes more uniform with their gas diffusion in the membrane electrode. In Figure 13a, the water is concentrated in the lower part of the flow field because of the product of the electrochemical reaction and the accumulation in the flow channels without bosses, and that shows a high risk of flooding. As shown in Figure 13b,c, the distribution of water is more uniform, and the area with a high value of water mass fraction
is also less than in Figure 14a without bosses. In addition, that shows a good drainage performance of the schemes of juxtaposition and cross-arrangement.

![Mass fraction of H₂O](image)

**Figure 13.** Distribution of the water mass fraction. (a) Without bosses; (b) juxtaposition; (c) cross-arrangement.

![Average mass fraction of oxygen and water](image)

**Figure 14.** Average mass fraction of oxygen and water.

As shown in Figure 14, the average mass fraction of water and oxygen is 17.17% and 8.11% without bosses, the one of water and oxygen is 13.69% and 11.36% with juxtaposition, and the one of water and oxygen is 13.28% and 11.75% with the cross-arrangement, respectively. Obviously, the water mass fraction of the two schemes with bosses is lower, and the oxygen mass fraction of the two schemes with bosses is higher than the schemes without bosses. In addition, according to the analysis above, the two schemes with bosses are more suitable for the uniformity of the gas in the flow field.

Generally, the low value of the oxygen mass fraction in the GDL means that the oxygen was consumed in the local area by the electrochemical reaction. Since the total amount of oxygen in the local MEA is not sure, the actual amount of water and oxygen in the area could not be determined according to the analysis above in different schemes. In addition, in this paper, the water content and oxygen content in the GDL and in the membrane were analyzed in different ways. The higher value of oxygen content means a better performance of gas diffusion, and the lower value of water content means a better performance of water drainage and a lower risk of flooding in the GDL. In addition, the higher value of water content means better performance in transferring hydrogen ions and a smaller Ohmic
resistance in the membrane. As shown in Table 4, the bosses in flow channels increase gas diffusion and water drainage. In addition, cross-arrangement is better than juxtaposition.

Table 4. Oxygen content and water content in GDL and the membrane.

<table>
<thead>
<tr>
<th></th>
<th>Water Content in GDL (kg/m³)</th>
<th>Oxygen Content in GDL (kg/m³)</th>
<th>Water Content in Membrane</th>
</tr>
</thead>
<tbody>
<tr>
<td>No boss</td>
<td>6.97 × 10⁻⁷</td>
<td>4.40 × 10⁻⁷</td>
<td>7.66</td>
</tr>
<tr>
<td>Juxtaposition</td>
<td>5.94 × 10⁻⁷</td>
<td>5.62 × 10⁻⁷</td>
<td>11.38</td>
</tr>
<tr>
<td>Cross-arrangement</td>
<td>5.77 × 10⁻⁷</td>
<td>5.88 × 10⁻⁷</td>
<td>11.46</td>
</tr>
</tbody>
</table>

In summary, the bosses could improve the distribution uniformity of reactant gas and water in the flow field, according to the analysis above. The cross-arrangement shows a better improvement in the performance of the fuel cell and is more suitable for this kind of flow field.

3.1.4. Influence on the Distribution of Temperature

The heat is generated from the electrochemical reaction in the catalyst layer. Therefore, the following analysis is based on the catalyst layer. As shown in Figure 15, there are obvious differences in the temperature distribution of the flow field between the three schemes. In Figure 15a, the area with high temperature is located in the middle of the flow field, and the shape of that area is similar to the dividing line between two areas of different colors in Figure 15a. The reason is that the electrochemical reaction in that area consumes oxygen and hydrogen, generates water, and releases heat rapidly. In addition, the heat of the reaction was carried to the lower part of the flow field with the flow of oxygen. As shown in Figure 15b,c, the schemes of cross-arrangement and juxtaposition show better uniformity in the distribution of temperature in the flow field. The bosses improve the uniformity of the distribution of oxygen and hydrogen, and the reaction rate in the whole flow field tends to be uniform. Therefore, the bosses improve the uniformity of the distribution of water and temperature. Compared with Figure 15b, the scheme of cross-arrangement shows a better uniformity of temperature in the flow field in Figure 15c, which could extend the life cycle of the fuel cell.

![Temperature distribution of different schemes.](image-url)  
(a) Without bosses; (b) juxtaposition; (c) cross-arrangement.
As shown in Figure 16, the average temperature, maximum, minimum, and maximum temperature differences in the flow field are 344.21 K, 351.45 K, 339.77 K, and 11.68 K, respectively, in the scheme without bosses. The average temperature, maximum, minimum, and maximum temperature differences in the flow field are 343.47 K, 346.66 K, 341.73 K, and 4.93 K, respectively, in the scheme of juxtaposition. The average temperature, maximum, minimum, and maximum temperature differences in the flow field are 343.39 K, 346.34 K, 341.12 K, and 5.23 K, respectively, in the scheme of cross-arrangement. The average temperature of the three schemes is similar. However, the maximum temperature and the maximum temperature difference of the scheme without bosses are much higher than the other two schemes. Serious damage would occur in the part of the flow field with high temperatures. In addition, a high maximum temperature difference in the flow field means severe power loss for the fuel cell. Thus, the schemes of juxtaposition and cross-arrangement are much more suitable, and the scheme of cross-arrangement is slightly better than the other for the flow field.

![Figure 16](image-url)

**Figure 16.** Average, maximum, and maximum temperature difference of schemes.

### 3.2. Influence of Boss Height

#### 3.2.1. Influence on the Distribution of Pressure Drop

Figure 17 shows the flow field pressure drop with different boss heights. The cross-section of the pressure drop diagram taken is the middle section of the cathode flow field, which can best represent the pressure drop distribution of the whole flow field. Since the total height of the flow channel is 0.6 mm, when the boss height is 0.2 mm, the middle section of the flow field is smooth and unbroken, as shown in Figure 17a; when the boss height is 0.4 mm and 0.6 mm, the middle section will cut to the boss, and the flow field section presents a discontinuous state, as shown in Figure 17b,c. As Figure 17 shows, the higher the height of the boss, the greater the flow field pressure drop. When the height of the boss is 0.6 mm (then the boss completely blocks the flow channel), the flow field pressure drop rises rapidly, and the maximum pressure drop is close to 170,000 Pa. When the flow channel is not completely blocked by the bosses, the distribution of pressure drop gradually decreases from the left to the right of the flow field. When the flow channel has been completely blocked by the bosses, the pressure drop of the whole flow field presents a stepped distribution from left to right. The reason is that after the boss is completely blocked in the flow channel, the gas can only be transmitted through the gas diffusion layer, and the transmission speed is slower than that without blockage. Therefore, the pressure in each part of each enclosed space makes little difference. However, there is a large pressure difference between different enclosed spaces, which presents an obvious ladder-form distribution.

Table 5 shows the average pressure drop of the flow field with different boss heights. With the increase in boss height, the average pressure drop at the inlet and outlet of the flow field gradually increases, and the higher the boss height, the faster the flow field pressure drop rises. When there is no boss, the flow field pressure drop is 593.15 Pa; when
the boss height is 0.2 mm, the flow field pressure drop is 779.66 Pa; when the boss height is 0.4 mm, the flow field pressure drop is 1479.34 Pa; When the boss completely blocked the flow passage, the average pressure drop of the flow field reached 165,000 Pa, which greatly increased the battery pumping loss of the fuel cell system.

![Image showing Pressure drop at different boss heights](image)

**Figure 17.** Flow field pressure drop at different boss heights. (a) Height is 0 mm; (b) height is 0.2 mm; (c) height is 0.4 mm; (d) height is 0.6 mm.

**Table 5.** Pressure drop of the flow field at different boss heights.

<table>
<thead>
<tr>
<th>Boss Height (mm)</th>
<th>0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure drop (Pa)</td>
<td>593.15</td>
<td>779.66</td>
<td>1479.34</td>
<td>165,328.68</td>
</tr>
</tbody>
</table>

An appropriate pressure drop in the flow field should be adopted to strengthen the convective transmission of reaction gas in the flow field and avoid a large pressure drop. The pressure drop when the boss height is 0.4 mm is more suitable for the flow field.

### 3.2.2. Influence on the Distribution of Flow Rate

Figure 18 shows the flow rate with different boss heights. The 61 flow channels are numbered. Adjacent numbered flow channels are adjacent in the flow field. In addition, the larger the number, the closer the flow channel is to the flow field entrance. As Figure 18 shows, the flow rate in the flow field channel at each boss height presents a “concave” trend. In addition, the higher the boss height, the less obvious the “concave potential” of the flow distribution. When the flow channel is completely blocked by the boss, the flow distribution is almost “horizontal”, without concave potential distribution. When there is a boss, the flow rate in the adjacent flow channel is distributed in an oscillatory manner, and the flow rate in the flow channel rises and falls with the increase of the number. In addition, the oscillation trend increases with the height of bosses increasing. When the boss completely blocks the flow channel, the flow rate of the “oscillating trough” is close to 0. The phenomenon above may be caused by the increase in boss height and the decrease in the section area of the flow channel outlet. The higher the height of the boss, the more fluid will be transmitted through the gas diffusion layer, and the greater the influence of the area of the exposed diffusion layer at the entrance on the flow rate. Given the exposed area of the adjacent reaction gas at the entrance of the diffusion layer shows an oscillation distribution, the above flow oscillation distribution phenomenon occurred. When the boss completely blocks the flow channel, the flow resistance of the adjacent flow channel at the
entrance is different. Almost all of the reactant gas is transported through the flow channel with low flow resistance.

![Figure 18. Flow rate of channels with different boss heights.](image)

SD (standard deviation of flow distribution) is also used as a dimensionless number to accurately measure the flow distribution uniformity of different boss heights.

Table 6 shows the standard deviation of flow distribution in flow channels with different boss heights. A smaller deviation shows better uniformity in the flow distribution. As shown in Table 6, the standard deviation of flow distribution decreases first and then increases with the increase in boss height. When there is no boss, the standard deviation (SD) is 0.1708. In addition, when the boss height is 0.2 mm, 0.4 mm, and 0.6 mm, the standard deviation SD is 0.1278, 0.0738, and 0.9984, respectively. When the boss height is close to 0.4 mm, the SD value is the minimum and the uniformity is the best. When the boss height is 0.6 mm (a completely blocked state), the SD value is the maximum and the uniformity is the worst.

Table 6. Standard deviation of flow distribution at different boss heights.

<table>
<thead>
<tr>
<th>Boss Height (mm)</th>
<th>0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD</td>
<td>0.1708</td>
<td>0.1278</td>
<td>0.0738</td>
<td>0.9984</td>
</tr>
</tbody>
</table>

3.2.3. Influence on the Distribution of Gas Components

Figure 19 shows the oxygen content distribution at the interface between the cathode gas diffusion layer and the catalytic layer with different boss heights. As shown in Figure 15, the oxygen concentration distribution at different boss heights generally presents a trend of a high value in the front and a lower value at the end. In addition, the uniformity of oxygen concentration distribution first increases and then decreases with the increase in boss height. Among the four schemes shown in Figure 19, the uniformity of oxygen concentration is the best when the boss height is 0.4 mm and the worst when there is no boss. When the bosses do not block the flow channel (boss height 0.2–0.4 mm) completely, there is no low oxygen concentration area at the front end of the boundary, and the low oxygen concentration area at the back end extends to the middle and gradually transitions to the high oxygen concentration area. When the bosses block the flow channel (boss height 0.6 mm) completely, the low oxygen concentration area appears at the front of the boundary. In addition, the low oxygen concentration area at the back end no longer extends to the middle but is concentrated and distributed in a straight line at the back end. Because
oxygen concentration is large and hydrogen concentration is small near the fuel cell air inlet, while hydrogen concentration is large and oxygen concentration is small away from the battery air inlet (near the battery hydrogen inlet), oxygen concentration distribution on the interface decreases. When the flow channel is completely blocked by the boss, the rate of oxygen transmission decreases, and more hydrogen is transferred to the end near the air inlet. At the same time, the oxygen concentration at the inlet end is large, and the reaction in this area consumes most of the oxygen, so the low oxygen concentration area is caused at the front end. When the bosses blocked the flow channel completely, the single flow channel was divided into many closed spaces. Reactant gas in different spaces could only be diffused through the gas diffusion layer, and the transmission resistance increased significantly. The oxygen concentration difference between different areas was obvious, so the low oxygen concentration area at the back end no longer extended to the middle and presented a straight line distribution, which was also the reason why the oxygen concentration distribution ladder was more obvious as shown in Figure 19d.

![Figure 19. Oxygen content distribution. (a) Height is 0 mm; (b) height is 0.2 mm; (c) height is 0.4 mm; (d) height is 0.6 mm.](image)

Figure 20 shows the distribution of water content at the interface of the cathode gas diffusion layer and the catalyst layer. The presence of bosses can significantly improve the uniformity of water distribution. In addition, the higher the boss height is, the smaller the area of high-water content is at the interface, which indicates that a higher boss could reduce the risk of flooding. The water content distribution tends to change from less near the air inlet end to farther away from the air inlet end, which is the reason why most flooding occurs far away from the air inlet end. As shown in Figure 20d, when the boss completely blocks the flow channel, a small area of high-water content will appear on one side of the inlet end. The reason is that the electrochemical reaction is violent and generates more water in a short time at this position.

Figure 21 shows the average material content at the interface of the cathode gas diffusion layer and catalyst layer, in which the average water content is 17.17% without bosses, 13.90% with a boss height of 0.2 mm, 13.28% with a boss height of 0.4 mm, and 12.88% with a boss height of 0.6 mm. The average oxygen content was 8.11% without bosses, 11.20% with a boss height of 0.2 mm, 13.28% with a boss height of 0.4 mm, and 11.64% with a boss height of 0.6 mm. As shown in Figure 21, with the increase in boss height, the substance content presents a trend that the water content decreases at first and then remains unchanged, while the oxygen content first increases and then remains unchanged, which indicates that when the boss height reaches a certain level, the influence
of height on substance distribution becomes smaller. The addition of bosses will increase oxygen content and decrease water content, indicating that bosses can improve oxygen transmission, increase the drainage performance of the flow field, and reduce the possibility of flooding.

![Mass fraction of H2O](image)

**Figure 20.** Distribution of water content. (a) height is 0 mm; (b) height is 0.2 mm; (c) height is 0.4 mm; (d) height is 0.6 mm.

![Substance content](image)

**Figure 21.** Average material content of different schemes.

Table 7 shows the comparison between the average content of material in the cathode diffusion layer and the content of water in the proton exchange membrane. The higher the height of the boss, the higher the content of oxygen in the diffusion layer and the content of water in the proton exchange membrane, indicating that the boss can improve the oxygen diffusivity in the fuel cell and reduce the membrane resistance to improve efficiency, and the higher the boss, the more obvious the effect. In addition, with the increase in height of the boss, the water content in the diffusion layer decreases first and then increases, indicating that the presence of the boss can change the state of the flow field and increase drainage performance. However, the higher the boss is, the more intense the reaction is, and more oxygen is converted into water, resulting in an increase in the water content in the diffusion layer. The change rate of each parameter in Table 7 increases with the increase in boss height and reaches its maximum value when the boss completely blocks the flow channel (height 0.6 mm).
Table 7. Material content of the diffusion layer and water.

<table>
<thead>
<tr>
<th>Bosses Height (mm)</th>
<th>GDL Water Content (kg/m³)</th>
<th>GDL Oxygen Content (kg/m³)</th>
<th>Membrane Water Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$6.97 \times 10^{-7}$</td>
<td>$4.40 \times 10^{-7}$</td>
<td>7.66</td>
</tr>
<tr>
<td>0.2</td>
<td>$6.01 \times 10^{-7}$</td>
<td>$5.53 \times 10^{-7}$</td>
<td>11.77</td>
</tr>
<tr>
<td>0.4</td>
<td>$6.32 \times 10^{-7}$</td>
<td>$5.69 \times 10^{-7}$</td>
<td>11.85</td>
</tr>
<tr>
<td>0.6</td>
<td>$7.78 \times 10^{-7}$</td>
<td>$8.69 \times 10^{-7}$</td>
<td>14.06</td>
</tr>
</tbody>
</table>

3.2.4. Influence on the Distribution of Temperature

Figure 22 shows the temperature distribution at the interface between the cathode gas diffusion layer and the catalyst layer with different boss heights. The bosses improve the uniformity of temperature distribution, which is conducive to extending the life cycle of the membrane. In addition, the addition of the boss enlarged the high-temperature area and reduced the maximum temperature, and the temperature showed an obviously stepped distribution with the boss distribution. The higher temperature in the area without bosses indicated that the oxygen diffusion state was better and the reaction was intense. When the boss blocks the flow channel (boss height is 0.2 mm and 0.4 mm) incompletely, there is a small area of the low-temperature area in front of the flow field. After the boss blocks the flow channel completely, the low-temperature area is transferred from the front end to the back end, which indicates that the former reaction is mainly concentrated in the back half of the part; hydrogen is consumed in the back half of the part; the front end reaction is not intense; the latter, due to the blockage of the flow channel, more hydrogen is transferred to the front and back ends and oxygen is reduced, resulting in cold areas.

![Temperature distribution](image)

Figure 22. Temperature distribution. (a) height is 0 mm; (b) height is 0.2 mm; (c) height is 0.4 mm; (d) height is 0.6 mm.

Figure 23 shows the maximum, minimum, average temperature, and maximum temperature differences at the interface of the gaseous diffusion layer and the catalyst layer at the cathode. From left to right, the temperatures in the figure are average temperatures of 344.21 K, 343.39 K, 343.44 K, and 343.65 K, respectively. The maximum temperature is 351.45 K, 346.34 K, 346.35 K, and 346.66 K; the minimum temperature is 339.77 K, 341.12 K, 341.16 K, and 341.28 K; and the maximum temperature difference is 11.68 K, 5.23 K, 5.19 K, and 5.38 K. The addition of the boss makes the maximum temperature decrease, the minimum temperature increase, the maximum temperature difference decrease, and the temperature of the whole interface more uniform, which is conducive to promoting the uniform reaction of each part of the battery and improving the service life of the proton...
film. In addition, the change in boss height has little influence on the temperature. When the boss height increases from 0.2 mm to 0.6 mm, the maximum temperature and minimum temperature both increase slightly, and the maximum temperature difference decreases first and then increases, but the range of change is small.

**Figure 23.** Maximum, minimum, average temperature, and maximum temperature difference.

In summary, the bosses increase the uniformity of internal temperature in the whole fuel cell, avoid local high or low temperatures, and improve the performance of the fuel cell. However, the range of changes is not obvious.

4. Discussion

4.1. Influence of Boss Arrangement on Fuel Cell Output Performance

According to the calculation results in Section 3.1 of this paper, the trend of fuel cell output characteristics of different schemes is similar, as shown in Figure 24. The order of current density and power density of different schemes, from large to small, is cross-arrangement scheme, juxtaposition scheme, and no boss scheme. Compared with the latter, the current density and power density of the former two schemes are significantly improved, indicating that the presence of a boss can greatly improve the output performance of the battery in the area of high current density. Compared with the two schemes with bosses, the output performance of the cross-arrangement scheme is higher than that of juxtaposition. As the internal loss of the battery under high current density is mainly concentration loss, the uniformity of reactant distribution in this region has the greatest impact on the battery’s performance. Through the analysis in Section 3.1, it has been concluded that the uniformity of reactive gas distribution increases in the order of no-boss scheme, juxtaposition, and cross-arrangement. Therefore, this trend in Figure 24 is consistent with the analysis in Section 3.1.

**Figure 24.** Battery output characteristics of different schemes.
Table 8 shows the comparison of the current density and power density of different schemes. The current density is selected near the rated working condition of the battery. The current density is taken at 0.6 V, and the power density is the maximum power density of different schemes, as shown in Figure 17. The power density value under the condition of 0.5 V is selected as the maximum value, and the percentage increase is based on the scheme without bosses. Compared with the scheme without bosses, the current density and maximum power density of juxtaposition increased by 11.45% and 20.26%, respectively. Cross-arrangement current density increased by 16.91%, and maximum power density increased by 25.00%. In contrast, the cross-arrangement scheme improves the battery’s output performance more.

Table 8. Current density and power density comparison.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Current Density (A/cm²)</th>
<th>Growth Rate of Current Density</th>
<th>Maximum Power (W/cm²)</th>
<th>Growth Rate of Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>no boss</td>
<td>1.137</td>
<td>—</td>
<td>0.692</td>
<td>—</td>
</tr>
<tr>
<td>juxtaposition</td>
<td>1.268</td>
<td>11.45%</td>
<td>0.832</td>
<td>20.26%</td>
</tr>
<tr>
<td>cross-arrangement</td>
<td>1.330</td>
<td>16.91%</td>
<td>0.865</td>
<td>25.00%</td>
</tr>
</tbody>
</table>

To fully understand the influence of different schemes on the output characteristics of the battery, it is also of great significance to analyze the current density distribution inside the battery. Figure 25 shows the distribution of current density on the surface of the cathode catalytic layer with different schemes. The high current density region as shown in Figure 25a is mainly concentrated in the middle of the battery, which is consistent with the distribution of the high-temperature region in Figure 25. Because the current transmission is faster than the temperature, the current density distribution can represent the actual distribution of the electrochemical reaction better than the temperature distribution. This is also the reason why the boss region boundary of the current density distribution is clearer than the temperature distribution. Overall, the current density distribution of the schemes is more reasonable, as shown in Figure 25b,c. Compared with the two schemes, the ones shown in Figure 25c are more suitable for application in fuel cells.

Figure 25. Current density distribution at the interface in each scheme. (a) without bosses; (b) juxtaposition; (c) cross-arrangement.
Through the above analysis, it can be concluded that, compared with the other two schemes, the scheme of cross-arrangement can improve the performance of fuel cells more. Therefore, this part of the exploration of the influence of boss height is based on the cross-arranged scheme.

4.2. Influence of Boss Height on Fuel Cell Output Performance

Figure 26 shows the output characteristics of the fuel cell with different boss heights. As shown in Figure 26, the bosses improve the current density and power density of the fuel cell significantly, especially in the area with high current density, where the transmission of reactants has the greatest impact on the fuel cell’s performance. Therefore, the bosses can improve the fuel cell’s performance in the area dominated by concentration polarization. With the increase in boss height, the current density and power density increase gradually, and the increased speed first becomes faster and then becomes slower. As shown in Figure 20, there is a large change in battery performance after the boss is added, and a small change in battery performance when the boss height is increased from 0.4 mm to 0.6 mm, but the change is larger than that when the boss is increased from 0.2 mm to 0.4 mm. It shows that the addition of the boss and the complete blockage of the boss in the flow channel both cause great changes in the internal flow field, promote the electrochemical reaction, and improve the performance of the fuel cell.

![Graph showing the output characteristics of the fuel cell with different boss heights.](image)

**Figure 26.** Fuel cell output characteristics with different boss heights.

To better measure the improvement of boss height on fuel cell performance, the improved data on performance are listed as shown in Table 9, where the current density is taken near the rated operating condition. The current density is taken when the voltage is 0.6 V. As shown in Figure 26, the maximum power density appears near the 0.5 V operating condition. The power density at 0.5 V represents the maximum power density value, and the reference of current density and power density increase percentage is the no boss scheme shown in Table 9. As shown in Table 9, the fuel cell performance gradually increases with the increase in boss height and reaches its maximum value when the boss completely blocks the flow channel.

**Table 9.** Current density and power density.

<table>
<thead>
<tr>
<th>Boss Height (mm)</th>
<th>Current Density (A/cm²)</th>
<th>Growth Rate of Current Density (%)</th>
<th>Maximum Power (W/cm²)</th>
<th>Growth Rate of Power Density (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.1373</td>
<td>—</td>
<td>0.6919</td>
<td>—</td>
</tr>
<tr>
<td>0.2</td>
<td>1.3296</td>
<td>16.91%</td>
<td>0.8818</td>
<td>27.44%</td>
</tr>
<tr>
<td>0.4</td>
<td>1.3503</td>
<td>18.73%</td>
<td>0.8899</td>
<td>28.61%</td>
</tr>
<tr>
<td>0.6</td>
<td>1.4363</td>
<td>26.30%</td>
<td>0.9125</td>
<td>31.87%</td>
</tr>
</tbody>
</table>
Figure 27 shows the current density distribution at the interface between the cathode gas diffusion layer and the catalyst layer with different boss heights. Compared with Figure 27a, the bosses make the current density distribution more uniform. According to Table 8 and Figure 27, the difference in current density increase between different boss heights is less than 10%. Thus, the difference in current density between different schemes is not obvious on the contour plot. However, the distribution still presents a low current density area in front of the flow field. When the bosses block the flow channel completely, the low current density area appears in the rear of the flow field.

Figure 27. Current density distribution. (a) Height is 0 mm; (b) height is 0.2 mm; (c) height is 0.4 mm; (d) height is 0.6 mm.

5. Conclusions

In this paper, we establish different numerical models and calculate the influences of different boss arrangements and boss heights on the uniformity of gas distribution. We also discuss temperature distribution and output performance of the fuel cell. Finally, the conclusions are as follows.

(1) The bosses increase the pressure drop of the flow field in the fuel cell, and the pressure drop of the flow field increases with the increase in the boss height. In addition, the pressure drop reaches its maximum when the bosses block the flow channels completely. The pressure drop with the boss arrangement of juxtaposition is much higher than that with the cross-arrangement because of the flow resistance.

(2) The bosses improve the distribution uniformity of each channel significantly because of the increase in diffusion through the gas diffusion layer, including the reactive gases, water vapor, and reaction heat. The uniformity of reactive gases leads to the uniformity of water content and temperature in the flow field. The uniformity increases with the increase in boss height. However, when the flow channels are blocked completely (the boss height is 0.6 mm), the uniformity decreases sharply.

(3) The bosses improve the uniformity of the distribution of current density in the flow field and the current density. In addition, the increase is more obvious at the operating points at high current density. With the increase in boss height, the current density increases to its maximum value when the bosses block the flow channel completely.

(4) Considering the pressure drop in the flow field and the current density, the cross-arranged scheme and 0.4 mm boss height are the most suitable for the fuel cell with the flow field.
(5) Limitations exist in the experimental and numerical simulation. It is hard to measure the flow rate of every single flow channel in a fuel cell because of the small size of the flow channels. However, the aim of increasing the uniformity of reactive gases is to increase the current density. In further research, a single fuel cell with an anode plate consisting of a special printed circuit board (PCB) could be made to measure the current density. In addition, the measured current density could be contrasted with the simulation results for model validation and verification analysis.

Author Contributions: Conceptualization, G.Z.; methodology, G.Z. and Z.G.; software, Z.G.; validation, Z.G.; formal analysis, G.Z.; investigation, G.Z.; resources, K.S., S.B. and G.L.; data curation, H.C.; writing—original draft preparation, Z.G.; writing—review and editing, G.Z. and D.L.; visualization, D.L.; supervision, H.C.; project administration, K.S.; funding acquisition, S.B. and G.L. All authors have read and agreed to the published version of the manuscript.

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References
3. Rostami, L.; Nejad, P.M.G.; Vatani, A. A numerical investigation of serpentine flow channel with different bend sizes in polymer electrolyte membrane fuel cells. Energy 2016, 97, 400–410. [CrossRef]
6. Dong, P.; Xie, G.; Ni, M. The mass transfer characteristics and energy improvement with various partially blocked flow channels in a PEM fuel cell. Energy 2020, 206, 117977. [CrossRef]


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